(12) **EUROPEAN PATENT APPLICATION**

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(54) **Calibration system for a color reproduction device**

(57) A method and apparatus for on-line predicting an analytical model of a dynamically varying color reproduction device comprises recursively executing a parameter adjustment algorithm for updating the parameters to the analytical model. Parameter adjustment is computed based upon a measured error signal detected between a sensed signal detected from actual device output and with an insitu sensor, and the analytical model output. The adjustment algorithm is recursively executed until parameter convergence effects a minimal error measurement, at which time the updated parameters are identified as accurate within the selected parametric model.
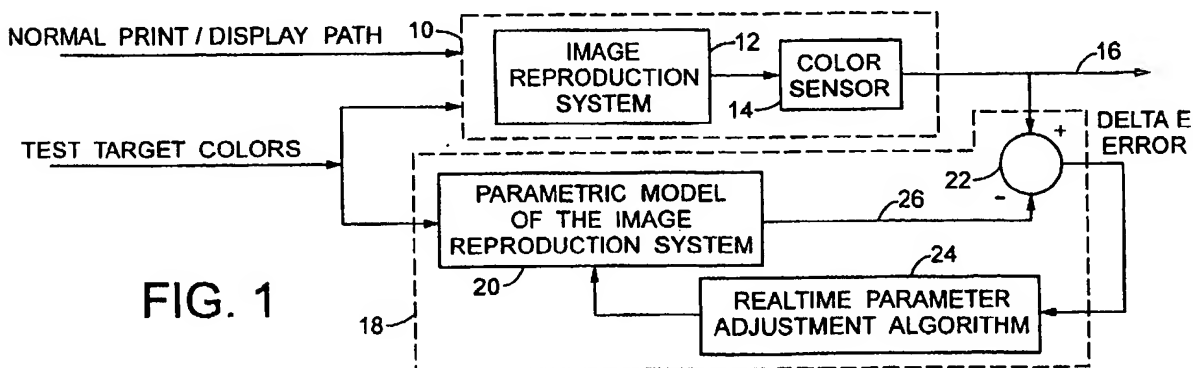
FIG. 1

Description

[0001] The subject invention pertains to the art of color management and image/text printing or display systems, and is especially applicable to a method and apparatus wherein a sensor monitors a color print output for on-line construction of an analytical model of printer operation. More particularly, the invention relates to system controls for modeling the printer by implementating an adaptive algorithm for estimation of analytical model parameters based upon processing of a relatively small number of control samples, target colors or other input signals, whereby the model is then useful for calibrating, diagnosing or standardizing operations of the printer.

[0002] Color correction and/or control should not be confused with color registration systems and sensors for insuring that colors are positioned properly, printed accurately, superposed correctly and/or adjacent to one another.

[0003] In today's business and scientific world, color has become essential as a component of communication. Color facilitates the sharing of knowledge and ideas. Companies involved in the development of digital color print engines are continuously looking for ways to improve the total image quality of their products. One of the elements that affects image quality is the ability to consistently produce the same quality image output on a printer from one day to another, from one week to the next, month after month. Colors on a printer tend to drift over time due to ink/toner variations, temperature fluctuations, type of media used, environment, etc. There has been a long felt commercial need for efficiently maintaining print color predictability, particularly as electronic marketing has placed more importance on the accurate representation of merchandise in illustrative print or display media.

[0004] Color perception is a psychological and physiological phenomenon that involves three elements: light, object and observer. Color changes as light, medium (i.e., paper, monitor) and observer interact. Color may be perceived differently under different types of lighting. Light sources that affect color include incandescent and fluorescent light. The first makes color seem more red and orange while the second emphasizes green and yellow tones. Different types of media also affect color perception. Paper is a medium that reflects color ink. In other cases the medium can be transmissive or emissive. Transparencies are an example of a transmissive medium while a computer monitor is emissive. The third element in the phenomenon is the observer. Different people may see the same color slightly differently. In order to characterize color image quality, the interaction of these elements must be understood so that when colors are intended to be matched, i.e., monitor to printer, scanner to printer, etc., acceptable appearance results.

[0005] For automatic control systems spectral data is often used to represent color perception as a pattern of wavelengths that leave the object before being interpreted by a viewer. Spectral data defines color independent of light and observer influence. A spectrophotometer is a sensing device used to measure spectral data.

[0006] There are different ways of representing color. One way color is described consists of the following parameters: hue, lightness and saturation. Hue represents the actual color wavelength (red, blue, etc.), lightness corresponds to the white content while saturation captures the richness or amplitude in color. Another way of describing color uses the three dominant primary colors red, blue and green (RGB). By combining these primary colors, in different intensities, most colors visible to humans can be reproduced. Monitors and scanners use the additive RGB color process. Printers use the subtractive CMYK (cyan, magenta, yellow and black) color process based on light reflected from inks coated on a substrate. The color representations described above fail to reproduce color predictably because they are observer or device dependent.

[0007] The functional models presented in this specification use a device independent color space to consistently track a set of target colors. L*, a*, b* are the CIE (Commission Internationale de L'éclairage) color standards utilized in the modeling. L* defines lightness, a* corresponds to the red/green value and b* denotes the amount of yellow/blue.

[0008] On-line model prediction is also known as "system identification" in automatic controls literature. It is the terminology used for the process of characterizing a given control system. Characterization of the system can be done in two ways; non-parametric and parametric In non-parametric system identification, the profile of the device can be measured by printing specific target colors as specified by the known standards. This profile is used as it is (without constructing any model of the device) while making rendering decisions/viewing of the customer colors on the monitor. This is one time measurement and does not use the historical information to construct any model. Whereas in the parametric system identification, predetermined target colors can be printed as chronological jobs in the banner sheet/header sheet or else the target colors can be extracted from the customer image and measured either by measuring straight from the output image or by rendering subset of customer colors as target color patches in banner or header page. Using the target colors and their measured counterparts, parameters of the model are adjusted on-line during each measurement. The intention in the parametric system identification is to adjust the parameters of the model and refine it over time by using past and present color data so that the model is what customers can use in their desktops. If such models can be incorporated on the smart color sensor, then the model can be exported to customer workstations.

[0009] As business and scientific environments continue to require increasingly complex printing capabilities, and especially more consistent and accurate color matching outputs, there is a continuing need for improved on-line modeling and calibrating of color printing devices. Prior systems which have suggested color modeling have been unable to recursively converge the model parameters continuously and efficiently. Current needs are better served with ana-

lytical model processing in a way that accurate parameters of a parametric model can be quickly identified through a recursive computation scheme. In a network printing environment such a need is particularly apparent for multiple prints which can come from different sources to different printers all networked to one another. Multiple printers could be of the same or different color marking technologies/colorants/materials linked to the same or different color gamuts. The multiple printer outputs being compared could even come from different types of printers, such as black and white, highlight color and process color printers. The principal problems exist when all of the prints from these different types of printers will not match or even be consistent from day-to-day. The problem domain grows by several orders of magnitude when the images are viewed under different lighting sources/viewing angles and are printed on different paper with non-optimum originals. Color differences produced on documents could also be due to stochastic errors on the images as they are produced by the devices of varying types, technology and media.

[0010] The subject invention is particularly useful to provide solutions to the foregoing color problems for a wide range of color workflow practices and particularly in customer environments with complex printing requirements. Printing and product enhancements are provided that would enable customers to manipulate color documents on a screen before even printing/displaying an output on different output devices in ways that improve the productivity of a current workflow by taking advantages of output color sensors constructed within the printing devices.

[0011] The subject invention exploits a key enabling factor for these operational advantages by constructing and maintaining a current analytical model of the reproducing device operation (also known as the device profile or characteristic, input-output model within the reproducible color). A knowledge of the characteristic/model of the device at the time of manipulating color documents is a precise dynamic model of the marking device. The subject invention provides a new and improved method for constructing such a dynamic model by using a color sensor mounted within the output device. When a customer has a need to accurately match the colors displayed or printed on various output devices, such as monitors (CRT, LCD, etc.) and printers (xerographic, ink jet, ionographic, etc.), he/she can get the most current analytical model of the particular output device by simply making a call request to the device or the repository where the analytical model is stored. Prior art systems have been known to use such color sensors offline to measure the most current profile of the device, e.g., an ICC profile. The subject invention improves on such sensor utilization by not only the mere acquisition of the ICC profile, but also the extraction of a dynamic parametric model using color information accumulated over a period of time. In other words, a recursive model of the printer is generated which by nature will be more accurate and up-to-date than a mere profile with one time measurement. A customer can use the analytical model in a soft-proofing package to make aesthetic decisions or rendering decisions across devices to produce the best reproducible colors - vivid or less vivid pictures, etc. Without having such an accurate dynamic model of the device, customer intentions/preferences cannot be met accurately, even though they can be conceived visually on a monitor. The subject invention provides for the creation and the effective wide spread use of such dynamic analytical models for devices that will enable consistent image reproduction initiated remotely across a system network.

[0012] In accordance with the present invention, there is provided a method and apparatus for on-line prediction of an accurate analytical model of a dynamically varying color reproduction device such as a printer. The device includes a sensor for detecting a signal representative of the device color output. The form of the analytical model is predetermined and preferably comprises a parametrical model comprising initially a random set of parameters. An image is produced with the device in response to an input signal. The sensor senses an output signal from the generated image representative of the image. The analytical model computes a model output in response to the same input signal. A difference or error is determined between the image output signal and the model output. Updated parameters are generated for the model from the prediction algorithm utilizing the determined error and are then applied as replacements to the model. The model is inverted and a subsequent input signal is transformed by the inverted model for adjusting the subsequent input signal therewith. The foregoing steps are recursively executed with a plurality of subsequent input signals until the determined error is less than a preselected value whereby the analytical model comprises an accurate representation of the device operation.

[0013] In accordance with another aspect of the present invention, the foregoing steps for generating the accurate set of parameters for the analytical model can be utilized to create a model for accurately calibrating a color printer during run time operation with only a relatively few number of parameter updating computations. The transforming of subsequent input signals with the inverse of the updated parametric model continually converges the parameter set until an accurate updated parametric model is determined. The subsequent images produced by the printer have input signals which are then calibrated by the inverse of the updated parametric model so that transformation of the input signal through the color printer results in a precise and accurate transformation of the input signal to the desired output signal.

[0014] In accordance with a more limited aspect of the present invention, the parameter adjustment through the generating of the updated sets of parameters utilizes a recursive convergent least square estimation algorithm incorporating the determined error between the image output signal and the model output.

[0015] In accordance with yet another more limited aspect of the present invention, the adjustment can be implemented with either known selected test target signals as the input signal, or normal print/display path operating input

signals.

[0016] In accordance with another aspect of the present invention, the analytical model, after successful updating, can be stored as a diagnostic program in a network system comprising a plurality of the reproducing devices. Devices in the network which generate an error greater than a certain selected value with the error computation steps above, are then recalibrated or repaired.

FIGURE 1 is a schematic/block diagram of a first embodiment of a on-line model prediction system wherein test target colors are primarily utilized for convergent model parameter updating;

FIGURE 2 is a schematic/block diagram of a system wherein normal print/display path input signals and test target signals are utilized for the generation of updated model parameters;

FIGURE 3 is a flowchart detailing the processing steps for on-line model construction in accordance with the subject invention; and

FIGURE 4 is a graphical representation of parameter convergence and consequent reduction in determined error by the implementation of the subject invention.

[0017] Referring now to the drawings wherein the showings are for purposes of illustrating the preferred embodiments of the invention only and not for the purposes of limiting same, the Figures show a method and apparatus for generating a dynamic device model automatically using an insitu color sensor. The model can be exploited as either a forward or inverse model. The invention has practical applications where a customer can use the dynamic device model by making a simple call to the device in a soft-proofing package to make aesthetic or rendering decisions on the input he/she supplies (e.g., graphics) to the printer. Without having the dynamic model of the device, customer intentions or preferences cannot be met accurately, although they can be conceived visually on a monitor. This type of model is especially beneficial when trying to accurately reproduce predictable color.

[0018] Figure 1 depicts a block diagram representation of the overall system for a first embodiment. The plant **10** specified in this system diagram consists of an ink marking device **12** and a color-sensing device **14**, although the invention is not restricted to ink marking devices alone and any image reproducing/displaying system such as printers, monitors or other imaging devices are intentionally included. In this application, the color-sensing device **14** is a spectrophotometer. The spectrophotometer provides the plant output **16** after capturing spectral information on the colors detected. The spectral information is a signal representative of the printed colors of the image and preferably comprises $L^*a^*b^*$ values, XYZ, Luv, etc., values depending on the desired color descriptions. For this description, only $L^*a^*b^*$ coordinate space values are used for describing color. A particular form of a parametric model is preselected off-line including a random parameter set before using the on-line model prediction steps of the invention to mathematically represent the plant **10**. If for some reason the functional form of the model is not adequate to describe the entire gamut of the color device **12**, then a partitioned model is used. The on-line system identification process will then switch between different functional models each corresponding to a partition of the gamut to update the parameters of the partitioned models depending on where the output colors are located in the printer gamut for given target colors. By cumulatively identifying the parameters of the partitioned models, a complete description of the device **12** will be constructed.

[0019] The actual on-line identification process on a sample- by- sample basis is described below. At first the default or initial random parameters are used to generate the error between the mathematical model and the actual device output (i.e., the measured colors). This error is then used inside an algorithm to update the parameters of the mathematical model. After updating the parameters of the model, the system identification loop will wait until after another set of measurements are available. Once they are available, again new errors are computed between the model output and the actual measurements. The model here will use the most current parameters. The error is then processed to compute the new set of parameters for the model. It is important to note that the error processing algorithm will determine how fast and how best the parameters are converged for a given functional model. This invention will use the convergent recursive least square estimation algorithm as the parameter estimator. It uses past and present data to compute the new set of parameters for the model. Thus measured data is processed sequentially as it becomes available to train the parameters of the model. It is also within the scope of the invention that the color processing can be represented by a plurality of analytical models each associated with a corresponding partition of a gamut of the reproduction device. The execution of the convergent algorithm would then comprise predicting, either on-line or with test target signals, a prediction of an accurate analytical model for each of the partitions.

[0020] With reference to Figure 3, and with continued reference to Figure 1, the processing steps for the on-line construction of the parametric model are illustrated. In the embodiment of Figure I, test target colors are fetched **30** and simultaneously inputted to the plant **10** and the processing system **18** which generates the parametric model. The image reproduction system 12 produces **32** a plurality of colors (either print or display medium) which are then measured **34** by the sensor **14** to generate an output signal comparable to the parametric model output signal. In this embodiment, L^*, a^*, b^* values of the printed target colors are measured as the output signal.

[0021]   The input signals received by the parametric model **20** are first transformed by the model in accordance with at least initially a random set of parameters fetched **36** from an associated base (not shown), but thereafter will be continually updated as the recursive processing steps are executed. The model **20** computes **38** L*, a*, b* values corresponding to the target colors utilizing the fetched parameters. Comparator **22** then computes **40** a deltaE error comprising a difference between the measured output signal **16** from the sensor **14** with the model output signal **26** from the model **20**. The deltaE error is then processed **42** through a selected parameter estimation/prediction algorithm **24** to obtain new parameters for the model **20**. The preexisting parameters are updated **44** in the database and then subsequently applied to the model for the processing of the next subsequent target color input signals applied to the system. It is a feature of the invention that the algorithm **24** will converge the parameters to a set which when applied to the model will eventually produce a deltaE error less than a predetermined value so that the on-line model will with reasonable accuracy predict the colors of the image reproduction system **12**.

[0022]   For the purpose of illustration, the simple linear model shown below is applied, but, of course, more complex parametric modeling selection of the reproducing system is within the scope of the invention

$$y = Mx + b \tag{1}$$

[0023]   The functional form of the mathematical model as that shown by Equation 1 above, is predetermined using input and output experimental data on the system. Once the best model is identified, we need to then tune the parameters of the model. For that, the adaptive algorithm is implemented to maintain the system specifications. In this illustration there are three inputs and three outputs (three input parameters to describe each input color and three output parameters to describe each output color). These inputs and outputs represent the L*a*b* values of a particular color. For simplification purposes, the input L_i^*, a_i^*, b_i^* will be referred to as x_1, x_2, x_3 and the output L_o^*, a_o^*, b_o^* as y_1, y_2 y_3. For this case Equation I can be expanded as follows,

$$y = A\hbar \tag{2}$$

where **A** is the regression matrix and $\hbar$ are the estimated parameters.

[0024] $A = [1 \ x_1 \ x_2 \ x_3]$

$$\hbar = \begin{bmatrix} b_1 & b_2 & b_3 \\ M_{11} & M_{21} & M_{31} \\ M_{12} & M_{22} & M_{32} \\ M_{13} & M_{23} & M_{33} \end{bmatrix} \tag{3}$$

To obtain the initial guess for the parameters, we use the standard batch least squares equation shown below.

$$\hat{\theta} = [A^T A]^{-1} A^T y \tag{4}$$

From this technique other parameter models can be built. For example,

partial quadratic model:

[0025]

$$A = [1 \ x_1 \ x_2 \ x_3 \ x_1^2 \ x_2^2 \ x_3^2] \tag{5}$$

quadratic model:

[0026]

$$A = [1 \ \chi_1 \ \chi_2 \ \chi_3 \ \chi_1^2 \ \chi_2^2 \ \chi_3^2 \ \chi_1\chi_2 \ \chi_1\chi_3 \ \chi_2\chi_3] \tag{6}$$

and cubic model:

[0027]

$$A = [1 \ \chi_1 \ \chi_2 \ \chi_3 \ \chi_1^2 \ \chi_2^2 \ \chi_3^2 \ \chi_1\chi_2 \ \chi_1\chi_3 \ \chi_2\chi_3 \ \chi_1^3 \ \chi_2^3 \ \chi_3^3]. \tag{7}$$

[0028] The recursive least squares (RLS) adaptive algorithm can be used to implement on-line system identification. It allows the machine to update the estimates of the parametric model while driving the error down to an acceptable level. Most adaptive algorithms are of the following form:

$$new\ estimate = old\ estimate + weight\ factor * error \tag{8}$$

[0029] The recursive least squares algorithm is no different. As mentioned above, the initial estimated parameters are determined from Equation 4. The next estimates, $\hbar_{k+1}$, are built by tagging the next set of input and output data points. a^T represents the regression matrix form for the next set of data while y is the following output a_k is a regression vector at a kth measurement interval. The regression for a_k is in the form shown by Equations 5, 6 or 7, depending on the choice of the model.

$$\hbar_{k+1} = \hbar_k + P_{k+1} a_{k+1} (y_{k+1} - a_{k+1}^T \hbar_k) \tag{9}$$

where P_{k+1} is,

$$P_{k+1} = P_k - \frac{P_k a_{k+1} a_{k+1}^T P_k}{1 + a_{k+1}^T P_k a_{k+1}} \tag{10}$$

[0030] The regression vector a_k as shown by Equations 9 or 10 is used for predicting parameters on-line whereas **A**, the regression matrix, is used for computing parameters once with input/output experimental data (initial guess when random parameters are not used.) The batch least square expression shown in Equation 4 may get used for the initial guess, and is not used for on-line parameter prediction.

[0031] Equations 9 and 10 achieved the on-line estimation by using the previous estimate and the error (y_{k+1} - $a_{k+1}^T \hbar_k$) between the outputs to converge to a new estimate. The convergence to a $\hbar_k$ is obtained when the error function is driven to zero or to a preselected desirable threshold value.

[0032] The embodiment of Figure I is primarily concerned with utilizing test color targets as the input for the on-line construction of the parametric model parameters. After such parameters have been converged to a desirable set, the model can be stored as part of a diagnostic program in a network system comprising a plurality of the reproducing devices. Devices in the network that would generate an error greater than a certain selected value are then recalibrated with new or the same test target color inputs. Alternatively, the model can be ported to a web or network system for communication to customer desktops on demand. The model can be embedded as a routine call request in a new service paradigm of future systems. Such calls can be part of document portals.

[0033] With particular reference to Figure 2, an alternative embodiment of the invention is illustrated wherein the input signals are on a normal print/display signals path and are then preliminarily transformed by an inverted form **50** of the parametric model for further processing as in the embodiment of Figure I. In this embodiment, the sequential application of the inverted form of the model and then the model itself to input signals, which together with the plant **16** will result in an identity transformation, provided the inverted model **50** is the inverse of the most current model obtained from the model construction block **18**. So long as the computed parameter set fails to construct a parametric model accurately mimicking the processing operation of the reproduction device **12** then an unacceptable deltaE error will be

detected as a difference between the device **12** output and the model **20** output.

[0034]   Such difference will continue to result in parameter adjustment by the adjustment algorithm **24**. The embodiment of Figure 2 is particularly useful not only as a diagnostic tool but as a method of on-line calibrating an image production system without human or operator involvement. Test target color inputs, although similarly applicable, are not necessary as the system can run as a continuously operating calibrating assembly.

[0035]   Yet another alternative embodiment is illustrated in Figure 2 wherein test target colors are used to construct the paramteric model, by bypassing the inverted model **50**. In this case, after the model **20** is deemed suitably accurate, the inverted form **P** $^{-1}$ is constructed for calibrated generation of either an LUT for on-line operation (such an LUT would be considered to be within block **50**), or it is also foreseeable that the inverted model **P** $^{-1}$ itself could be used for input signal adjustment and resulting improved accuracy in color reproducing.

[0036]   The test consisted of an actual implementation (Xerox DC40) that printed a number of color patches. The number of patches and colors are selected from the open loop simulation of the parametric model. Thirty-three different input target colors were selected and are graphed in Figure 4. For illustration purpose, a cube in the input gamut was selected which covered about 60% of the reproducible space. Target colors were printed and read by a spectrophotometer in real-time. The output of the spectrophotometer represents the plant output **16** in Figure 1. It is converted into L*, a*, b* coordinates and fed into the RLS algorithm. The performance index used was deltaE, where λE is the square root of the sum of the errors squared.

[0037]   The best results were obtained with the quadratic and cubic model. Each curve represents the λE for a particular target color. After convergence was reached the mean λE and $\rightarrow$ for quadratic model was 2.04 and 0.91, respectively. However, the cubic model showed an improved mean of 1.71 and $\rightarrow$ of 0.76. These results show that one can use a series of target colors in a very effective manner to predict the forward model of the device. DeltaE for a cubic Linear-In-The-Parameter model is shown in Figure 4. Importantly, it can be seen that convergence to an acceptable error was realized after only six to eight prints were executed for each color.

Claims

1. A method for online predicting an analytical model for a dynamically varying color reproduction device including a sensor for detecting a signal representative of device color output, wherein color processing of the device is represented by a preselected form of an analytical model comprising initially an inaccurate set of parameters, the method including steps of:

     producing an image with the device in response to an input signal;
     sensing with the sensor an output signal representative of the image;
     computing from the model a model output in response to the input signal and comparable to the image output signal;
     determining an error between the image output signal and the model output;
     generating an updated set of parameters for the model from a prediction algorithm utilizing the error and applying the updated set to the model; and,
     recursively executing said steps with subsequent input signals until said error is less than a predetermined value whereby the analytical model including the updated set of parameters comprises an accurate representation of device operation.

2. The method as defined in claim I wherein the generating comprises converging the inaccurate set to the updated set with less than ten recursive executions of said steps.

3. A color printer comprising:

     an image reproduction system for generating an output image in response to an input signal;
     a sensor for detecting a sensor signal representative of the output image; and,
     a processor comprising:

       a parametric model of the image reproduction system for transforming the input signal into a model output;
       a real-time parameter adjustment algorithm;
       an inversion of the parametric model; and,
       a comparator for comparing the sensor signal with the model output, wherein based upon an output from the comparator, the real-time parameter adjustment algorithm computes an updated set of parameters for the parametric model and the inversion of the parametric model, and the model and inversion are

updated in accordance with the updated parameters, for recursively transforming a subsequent input signal with the updated inversion and the updated model.
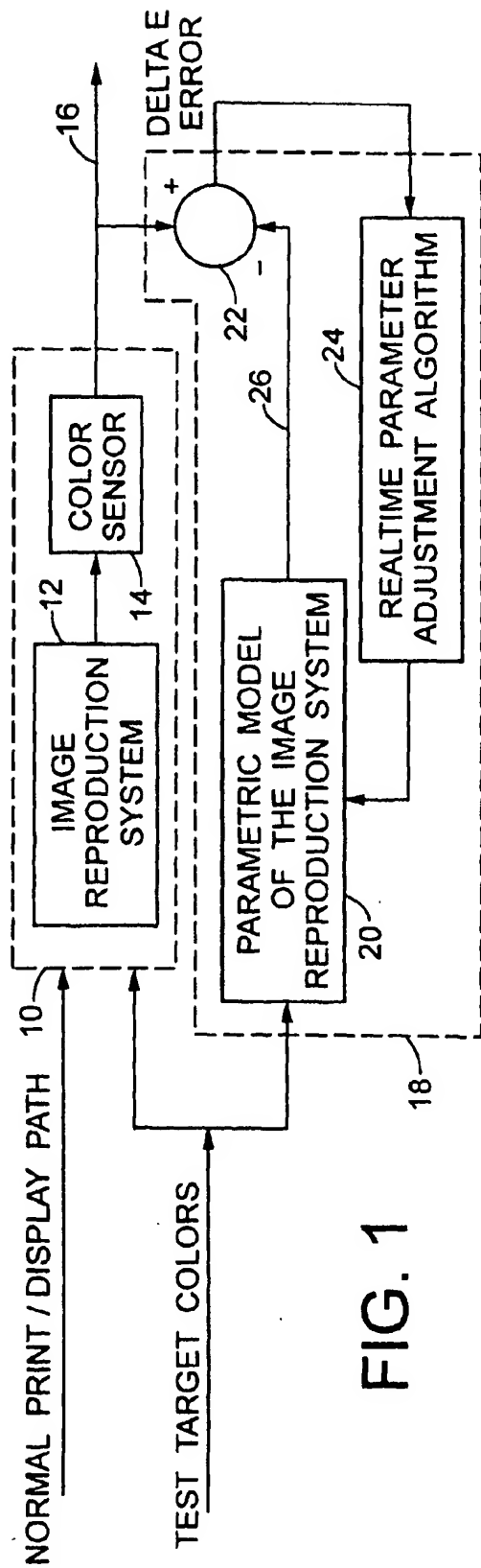
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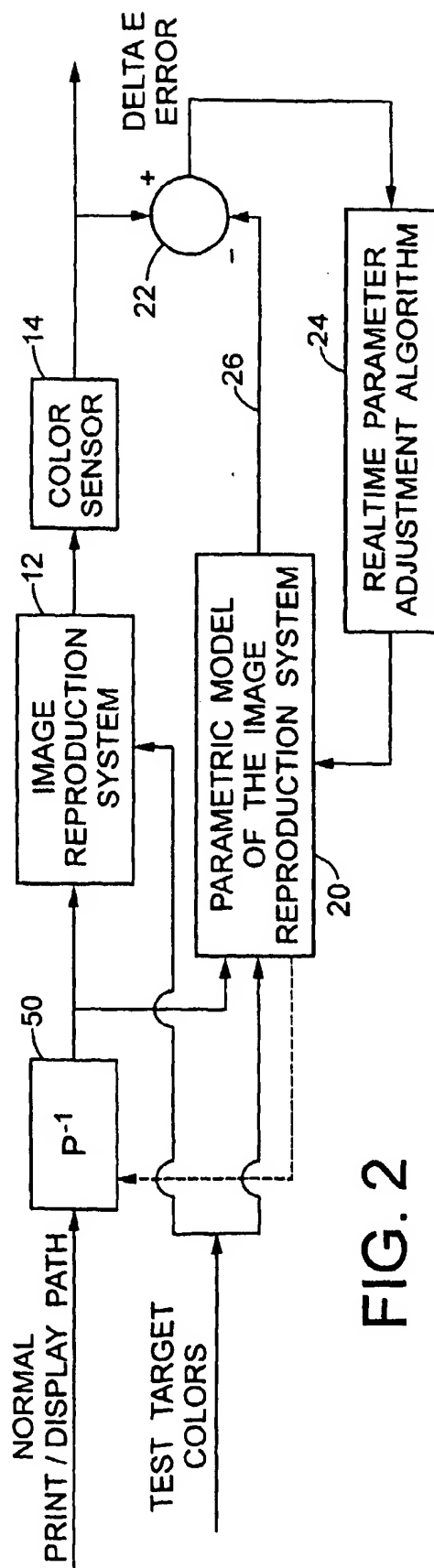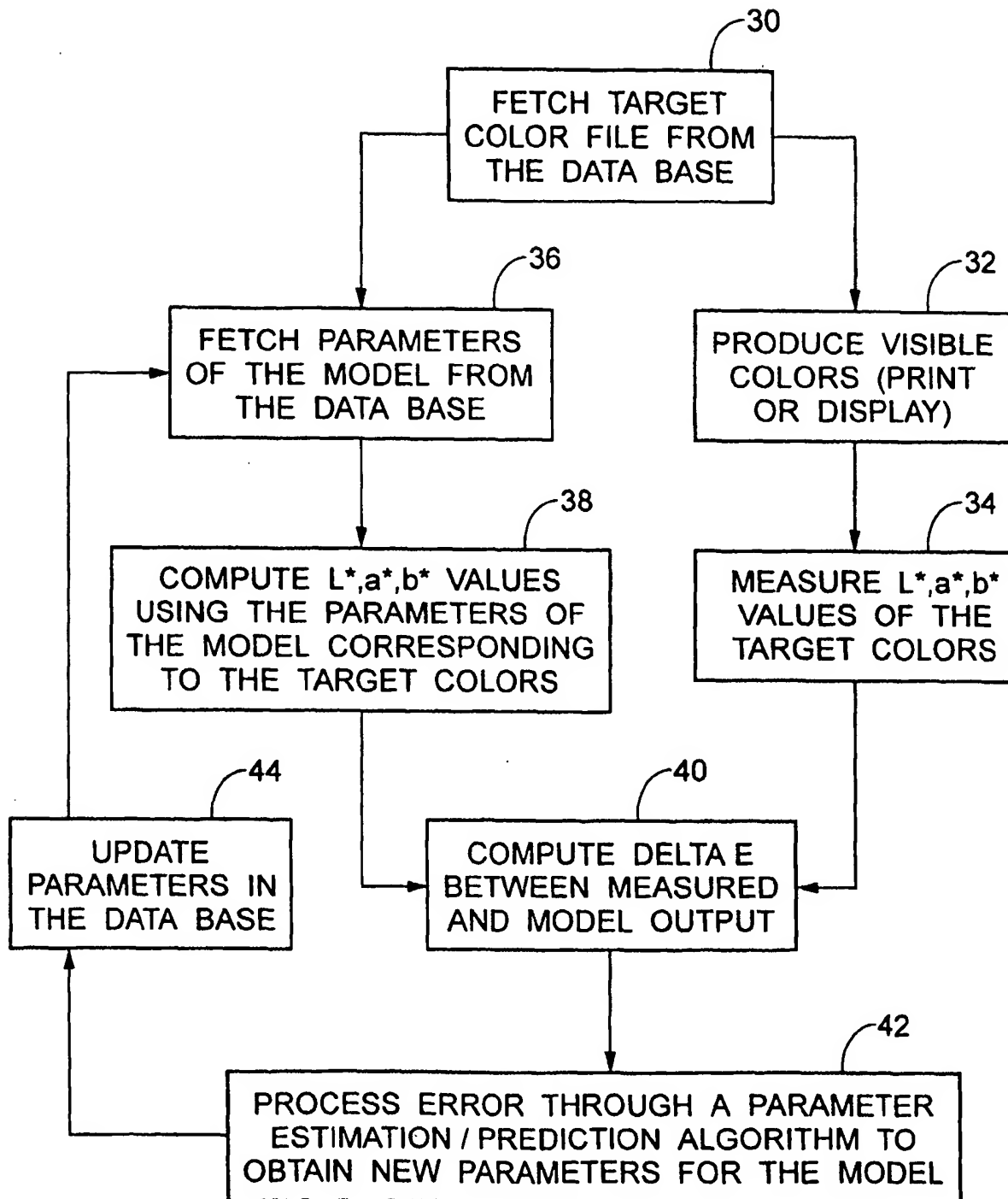30

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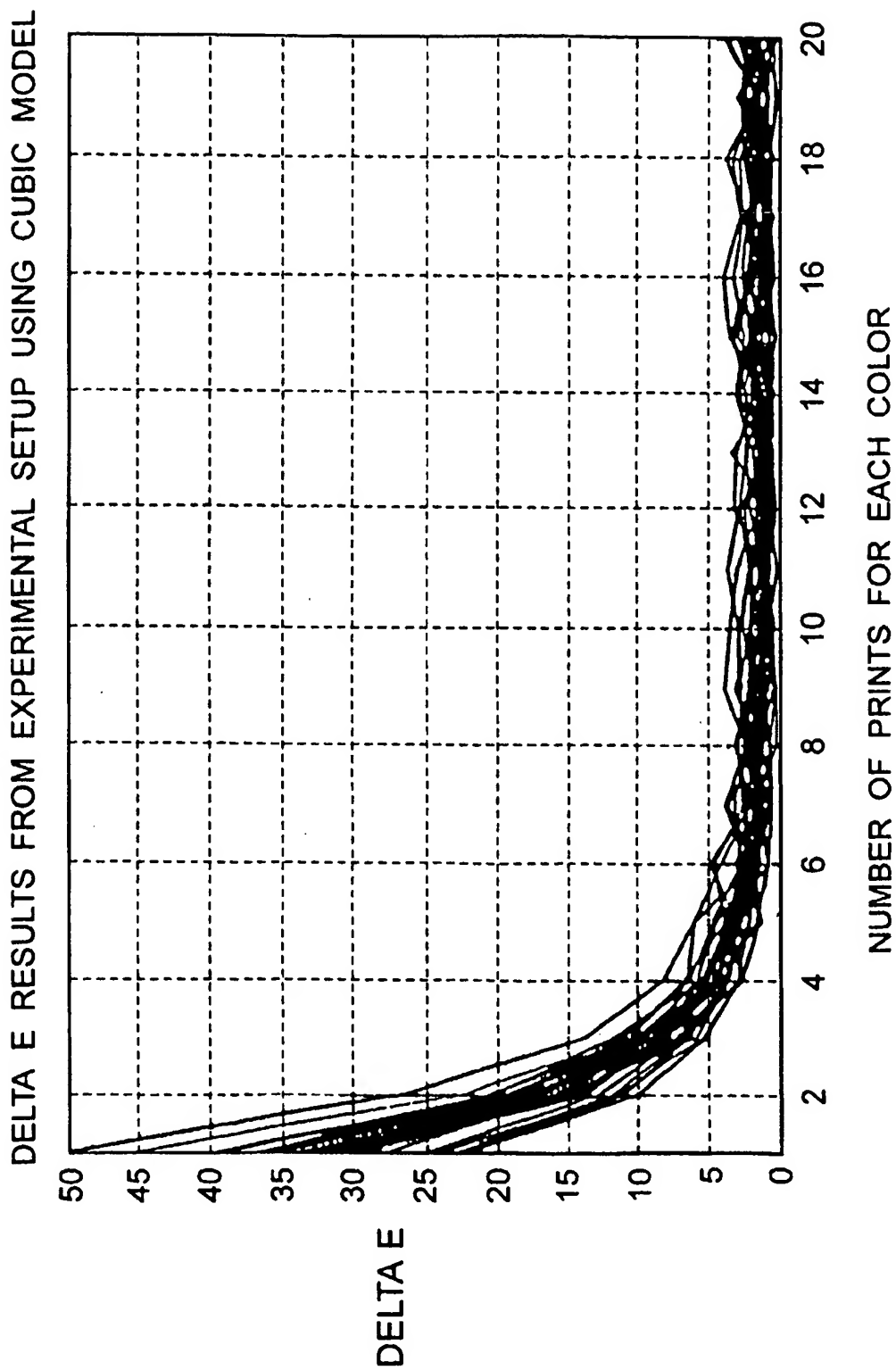50

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FIG. 1

FIG. 2

FIG. 3

DELTA E RESULTS FROM EXPERIMENTAL SETUP USING CUBIC MODEL

NUMBER OF PRINTS FOR EACH COLOR

FIG. 4

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